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**Original scientific paper**

# TECHNO-COMMERCIAL VIABILITY OF HYBRID SOLAR-BATTERY PROJECTS FOR DISTRIBUTED GRIDS WITH TIME-OF-DAY TARIFFS

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**Abstract:** *In India, the central Government, as well as the respective states, have laid out policies to encourage the adoption of solar energy. For many types of consumers, especially residential and commercial, the Levelized Cost of Energy (LCOE) of solar energy is lesser than the cost of energy imported from the grid. However, solar energy is an intermittent and variable resource, which cannot fulfil the load at all times. Addition of battery storage energy systems (BESS) to solar PV projects can help the consumer better meet their load profile through renewable energy, while improving grid resilience. In many states, time-of-day (ToD) tariffs are offered, which provide incentives for exporting energy beyond sunlight hours. It has been postulated that with ToD tariffs, and falling battery prices, addition of storage can provide benefits to the customer. However, it needs to be analyzed whether hybrid solar-battery storage configurations would make financial sense. In this study, we compare the performance of two popular battery types, Lead Acid and Lithium Ferro Phosphate (LFP), to see which battery type would provide better economic returns for the given customer. The impact of parameters like round trip efficiency, replacement State of Health (SOH), maximum State of Charge (SOC) and cycle time have been considered. It is shown that for current market tariffs and prevalent battery costs, addition of batteries does not improve the Net Present Value (NPV) for residential or commercial customers. The best returns are obtained when the system has only solar, with no batteries attached, while commercial systems achieve better NPV as compared to residential customers. The highest NPV for a residential customer is $1847 for a 6.6 kW system for the given load profile and tariff regime. In contrast, the highest NPV for a commercial customer is $4165 for a 7.7 kW project. It is seen that accelerated depreciation benefits play a major role in improved returns from commercial installations. It is also seen that retail rate dispatch provides higher returns as compared with the peak shaving and self-consumption dispatch algorithms, since it reduces both energy as well as demand charges. It is demonstrated how the retail rate dispatch modulates the battery*

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*discharge & charge configuration every hour considering the prevalent tariff at that time and the energy left in the battery.*

**Key words**: *Solar PV, Battery storage, Hybrid systems, NPV, Retail rate dispatch, LFP batteries*

## 1. INTRODUCTION

Integration of battery storage with PV can add value to the customer in numerous ways. Adding BESS can maximize PV self-consumption by using excess solar power for charging batteries, and reducing grid import at other times to meet load demands. Curtailment of PV generation can be avoided by using batteries to store the surplus power. Due to these benefits, the Indian Government is actively promoting battery adoption at various levels, including utility, commercial & residential scales. BESS can also help in energy cost arbitrage, by charging during off-peak periods and discharging during peak hours [1]. Chatzigeorgiou et al have done a detailed review of the benefits afforded by hybrid PV-BESS installations. They have considered the economic returns from solar-storage hybrid projects in several countries; however, India is excluded from their review. Residential storage is viable in countries like Switzerland, Spain, Norway & Germany, however it proved unviable in countries like Australia & Ireland as per the policies extant at the time of review [2]. Goulart proposes that the economic value of all the different ancillary services should be considered and stacked together to give a true picture of economic gains. They calculated the stacked benefits of load shifting and peak shaving using BESS for a project in Brazil and found that 97% of the revenue share comes from load shifting [3]. Wanapinit calculated the impact of residential PV coupled with battery storage on system generation costs in Germany. They studied the respective generation costs when storage is used to provide peak-load shifting, self-consumption and energy arbitrage services respectively [4]. Wu has compared the impact of different dispatch strategies (maximum self-consumption, time-of-day, fully fed to the Grid) on energy costs, self-sufficiency and self-consumption for a PV-battery system connected to a typical household in Denmark. They found that self-consumption strategy leads to the lowest purchased energy costs but is applicable only in areas where energy spot prices are high. In contrast, time-of-day (ToD) strategy is more suitable for areas with maximum differential between peak and non-peak tariffs [5].

Bagalini [6] conducted a Net Present Value analysis of a system with Solar PV and batteries in China. Their analysis for a residential building showed that the project was not viable economically viable due to a combination of low electricity prices, and high battery costs. Hassan et al. [7] have computed the optimum size of solar PV and the corresponding battery capacity for maximum self-consumption for a project in Iraq. Khah [8] calculated the optimum battery sizing to calculate the ‘least cost of electricity’ for a residential project in Tehran, Iran. However, they did not consider battery degradation during the lifetime of the project. Another study by Heine used System Advisor Model (SAM) for sizing batteries for integration with residential buildings. They considered buildings across 4 different climatic zones in Arizona and found that maximum NPV is produced when batteries are sized 1.5 times the capacity needed for annual peak energy requirements. They also found that the best returns are achieved when batteries are sized such that replacement is not required during the PV system lifetime [9]. Rezaeimozafar [10] used a meta-heuristic algorithm instead of a rule-based algorithm to optimize BESS sizing and charge-discharge scheduling for a behind-the-meter (BTM) residential project in Ireland. The objective used for optimizing battery sizing was minimum installation cost, instead of parameters like LCOE or NPV, which consider the costs & returns over the lifetime of the project. The objective also had a boundary condition of minimizing electricity bills and battery degradation over the course of one year. Amin [11] analyzed the financial and technical viability of hybrid solar PV systems at the residential level.

Dhundhara [12] studied the cost for optimal system configuration by comparing hybrid systems using Lead Acid and LiFeSO4 batteries. They found that Lithium-Ion batteries are techno-commercially more viable in microgrid settings which included PV, wind turbine, diesel and biodiesel generators. Makola [13] evaluated the performance of both Lead Acid & Lithium-Ion batteries in a DC-coupled microgrid; however, they have not clarified the variant of Lithium Ion that has been used. They used ETAP software to analyze the performance of the batteries over a 24-hour period, considering parameters like usable capacity, efficiency, lifespan, c-rate, safety, etc. Townsend has compared important characteristics of battery behavior like energy density, power density, thermal runaway, maximum charge and discharge rates, cycle durability and cost for Lead Acid and Lithium-Ion variants. They propose changing the battery operating parameter from their initial values, as the battery degrades. Kebede [14] has done a techno-economic analysis comparing LCOE and NPV for Lithium Ion and Lead Acid batteries for storage applications using HOMER. They created an Equivalent Circuit Model in MATLAB to account for the impact of charging-discharging behaviour on battery capacity degradation. Reveles-Miranda et al [15] have reviewed the ability of battery storage systems to provide benefits through energy management, and ancillary services like power quality support and power systems protection, and non-technical benefits. They have also compared the respective pros and cons of using Lead Acid, Lithium-Ion batteries & supercapacitors in providing such services. The summarized contributions of the paper are as follows:

a) Viability of hybrid solar-storage systems analysed for residential as well as commercial consumers with variable time-of-day tariffs
b) Different dispatch algorithms evaluated to figure out the one that gives better financial returns
c) Impact of solar DC capacity, as well as different storage capacities on NPV calculated for residential as well as commercial customers
d) Compared financial returns of 2 battery types; Lead Acid and Lithium Ferro-Phosphate, and calculated their economic viability
e) Impact of retail rate dispatch shown on battery state of charge

## 2. THEORETICAL BACKGROUND

### 2a. Solar module modelling

The PV module power output is represented by Eq. 1, which shows that the PV module generation is directly related to the incident solar irradiation [16], where $P_{STC}$ is the rated power of solar PV system at standard test conditions (STC), $d_r$ is module derating factor, $G_{inc}$ is the solar irradiation falling on the solar module plane, $G_{incSTC}$ is the solar irradiation under STC conditions, $\alpha_s$ is the coefficient of temperature (%/ºC), $T_c$ is the solar cell temperature (ºC) as defined by Eq. 2, and $T_{cSTC}$ is the cell temperature under STC conditions. Here NOCT refers to the cell nominal temperature, while $G_{ref}$ is the reference solar irradiance of 0.8 kW/m2 [16]. Thus, the output of the solar PV generator ($P_s$) will vary throughout the day as the incident irradiation and cell temperature changes.

$$P_s = P_{STC} d_r \left(\frac{G_{inc}}{G_{incSTC}}\right) \lfloor 1 + \alpha_s (T_c - T_{cSTC}) \rfloor \quad (1)$$

$$T_c = \left(\frac{NOCT - 20°C}{G_{ref}}\right) (G_{inc}) \quad (2)$$

### 2b. Battery modelling

Eqs. 3-5 describe the relationship between the State of Charge (SOC) and the charging and discharging power values [17]. Where SOC(t) and SOC(t-1) represent the SOC at time t and (t-1) respectively; $SOC_{min}$ and $SOC_{max}$ are the minimum and maximum allowed SOC, Q(t) represents the charge capacity at time t, $Q_{max}$ the maximum charge capacity of the battery, $\eta_{ch}$ and $\eta_{dis}$ represent the energy storage charging and discharging efficiency respectively, $P_{ch}$ and $P_{dis}$ show the charging and discharging power to the energy storage battery, and $D_B$ is the self-discharge rate of the battery.

$$SOC(t) = SOC(t-1) + [\eta_{ch} P_{ch}(t) - D_B Q_{max}] \frac{\Delta t}{Q_{max}} \quad (3)$$

$$SOC(t) = SOC(t-1) + [-\frac{P_{dis}(t)}{\eta_{dis}} - D_B Q_{max}] \frac{\Delta t}{Q_{max}} \quad (4)$$

$$SOC_{min} \leq SOC(t) \leq SOC_{max} \quad (5)$$

The battery voltage can be derived from the SOC through Eq. 6. The no-load voltage of the battery VB is calculated based on the SOC of the battery using a nonlinear equation (Eq 6), where V0 is the battery constant voltage in V, K is the polarization voltage in V, Q is the battery capacity in Ah, and A and B are parameters determining the charge and discharge characteristics of the battery. The parameters A, B and K can be tuned to mimic a specific battery type discharge characteristic [18].

$$V_B = V_0 - K\frac{1}{SOC} + A^{-BQ(1-SOC)} \quad (6)$$

## 3. SOLUTION METHODOLOGY

### 3.1. System configuration

Chandigarh is a city in northern India, with mostly residential dwellings and commercial installations, located at latitude 30.75o N and longitude 76.75o E. For this analysis, we consider a residential consumer as well as a commercial installation in Chandigarh city in India. Fig. 1 describes the system considered for this study, which consists of solar PV modules with a PV inverter, battery storage with a battery inverter, and an active load within the customer premises. The batteries are connected to the solar PV through the AC bus in a BTM setup. The hybrid PV-battery system is connected to a distributed grid, with provision for exporting as well as importing power. The power flow in the system represented in Fig. 1 can be described by Eq. 7.

$$P_{PV}(t) - P_{Batt}(t) + P_{Grid}(t) = P_L(t) \tag{7}$$

$P_{PV}(t)$ - Power generated through PV, at time t
$P_{Batt}(t)$ - Power charged/discharged into BESS at time t
$P_{Grid}(t)$ - Power imported/exported from the Grid, at time t
$P_L(t)$ - Internal load requirement of the customer at time t

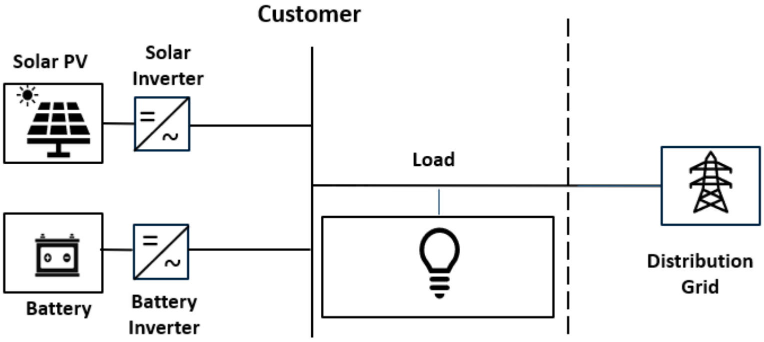

**Fig. 1** Schematic of customer with solar and battery storage connected to distributed grid

### 3.2. System parameters

A software product SAM model 2024.12.12 from the National Renewable Energy Laboratory (NREL) [19] was used for modelling hybrid solar-storage projects and calculating relevant financial parameters. The load profile for Chandigarh is taken from the India Climate & Energy (ICE) dashboard, which publishes annual load profiles for different locations within India [20]. Following the approach used by Bortolini and Tsai, the maximum yearly load value from the ICE data is normalized to 5kW, and the other values are prorated proportionately, so that we can get a yearly load profile for a residential customer with a maximum 5 kW load [21] [22]. The weather data for Chandigarh, including Diffuse Horizontal Irradiation (DHI), Global Horizontal Irradiance (HNI) and Ambient Temperature, is derived from the National Solar Radiation Database (NSRDB) maintained by NREL [23]. The weather data is provided in typical meteorological year (TMY) format, which consists of 8760 (24 x 365) hourly values for 1 year.

### 3.3. Component parameters

320 Wp modules (WSM-320) from Waaree Energies have been chosen for the PV system, while the PV inverter considered for the projects is model IQ8D-BAT with 638W max AC capacity, from Enphase Energy, with a CEC efficiency of 96.8%. For this study, two battery technologies are considered, Lead Acid (LA) and Lithium Ferro-Phosphate (LFP) batteries, which are a type of Lithium-Ion battery. The default technical parameters for these battery types available in SAM have been considered for this study and are obtained from a NREL report [24]. A summary of the differences in the values considered for Lead Acid and Lithium-Ion batteries in this study is given in Table 1 [25].

**Table 1** Comparison of operational parameters for Lead Acid and Lithium-Ion batteries

| Parameters | Lead Acid | Lithium Ion |
|---|---|---|
| Battery Type | VRLA Gel | LFP |
| Round Trip Efficiency | 84% | 92% |
| Battery bank replacement threshold (State of Health) | 80% | 80% |
| Cycles at replacement State of Health | 850 | 9186 |
| Minimum State of Charge | 50% | 20% |
| Maximum State of Charge | 95% | 95% |

### 3.4. Dispatch algorithm

The Battery Management System (BMS) can modulate the dispatch algorithm of the batteries, considering the stated objectives of the consumer. SAM offers different options for battery dispatch algorithms, including peak shaving, self-consumption, retail rate dispatch, etc. Analysis through SAM shows, that 'retail rate dispatch' provides better economic returns in the form of NPV, with respect to other dispatch algorithms and therefore has been considered as the default dispatch algorithm, as it helps to minimize the electricity bill for the customer, based on the cost of purchasing electricity from the grid in each time step. In this algorithm, the battery can charge from the grid as well as from PV modules. The battery will charge from the PV system only if it exceeds the load, and the battery will be discharged only if the load exceeds the PV generation, which conditions are described in detail by [26] [27]. The retail rate dispatch algorithm, also known as 'price signal forecast', has been evaluated in a paper by NREL [28].

Retail rate dispatch helps to minimize both energy & demand portions of the monthly electricity bill. In Peak shaving, the battery is dispatched to reduce daily peak demand. This option is helpful if the aim is to use the battery to reduce billing demand. Self-consumption algorithm dispatches the battery to minimize power to and from the grid [19].

The dispatch algorithm for charging and discharging the battery storage is represented in Fig. 2 [29]. This algorithm considers hourly tariff, as well as current power from PV, and state of charge of battery, where $P_{PV}$, $P_{Batt}$ and $P_L$ are defined as per Eq. 7. SOC is the current State of Charge of the given battery; $SOC_{max}$ & $SOC_{min}$ are the maximum and minimum State of Charge values possible for the battery; $Tariff_{max}$ and $Tariff_{min}$ are the peak and off-peak period tariffs respectively. The algorithm can be described as follows:

**Condition 1**: $SOC = SOC_{max}$; $P_{PV} > P_L$
**Action:** If battery SOC is at its maximum level, and PV generates more power than load requirement, excess power is exported to grid

**Condition 2:** $SOC = SOC_{max}$; $P_{PV} < P_L$
**Action:** In this case battery SOC is at its maximum level, and PV generates lesser power than load requirement. If current hourly tariff is at maximum tariff value, then battery takes precedence over grid import, and battery is discharged to take care of load. If current hourly tariff is lower than maximum tariff value, power can be imported from grid to take care of load.

**Condition 3:** $SOC < SOC_{max}$; $P_{PV} > P_L$
**Action:** In this case, battery SOC is below its maximum level, and PV generates more power than load requirement. Then, the battery is charged from solar. If excess power is still left, then remaining power is exported to Grid.

**Condition 4:** SOC < $SOC_{max}$; $P_{PV} < P_L$

**Action:** In this case, battery SOC is below its maximum level, and PV generates lesser power than load requirement. If current hourly tariff is at minimum tariff value, then battery can be charged from grid. If tariff is higher than minimum value, then battery is not charged from grid.

### 3.5. Financial parameters

Time-of-day tariff charges for different regions in India are published in a report by the Central Electricity Authority, Govt of India named ‘Electricity Tariff and Duty and Average rates of electricity supply in India’ [30]. The tariffs for the evening peak load period are 1.2 times the normal period tariffs, while the off-peak load tariffs are 0.9 times the normal period tariffs. Net metering regulations are applicable in Chandigarh as per the guidelines prescribed by Joint Electricity Regulatory Committee (JERC) [31].

The latest electricity tariffs applicable from Aug 2024 have been published in a tariff schedule by the Electricity Deptt of Chandigarh administration [32]. Table 2 defines the chargeable tariff slabs based on the time-of-day for residential and commercial consumers, as well as the tiers that define the slabs in kWh, under which the maximum usage falls. JERC defines the tariffs in Indian Rupees (INR) in units of INR/kWh, which have been converted to USD/kWh assuming an exchange rate of INR 85 = 1 USD. [32]. It should be noted that tariffs for commercial consumers are higher than those for residential consumers for each tier, because of the principle of cross-subsidy.

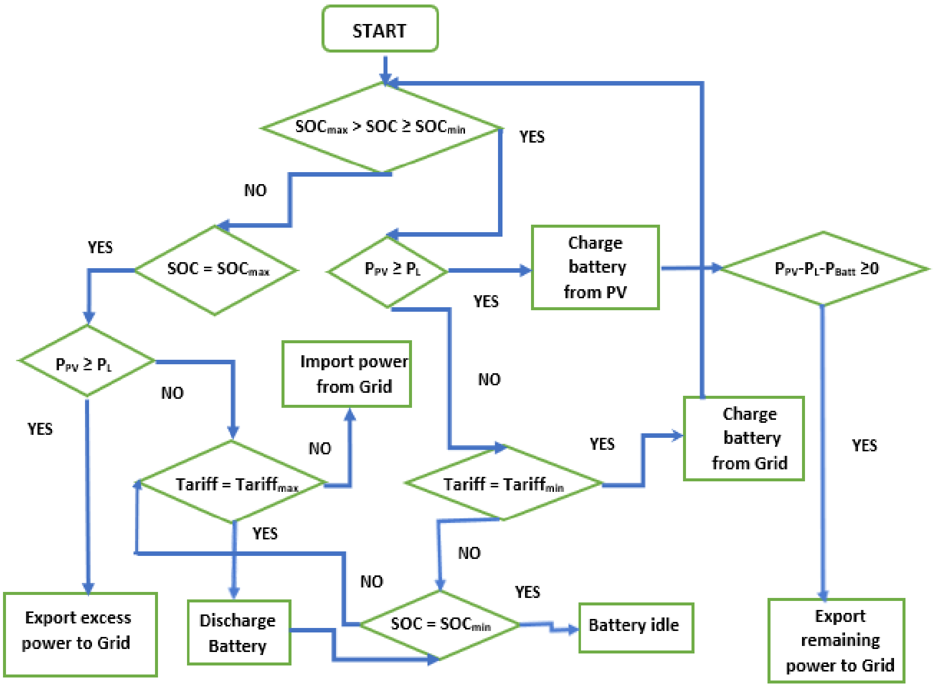

**Fig. 2** Flowchart for charging & discharging of battery storage with ToD tariffs

The buying and selling rates for electricity are considered as per Net Energy Metering option, since Net Metering regulations are applied to residential customers in Chandigarh [31]. In Net Metering, if the amount of electricity exported exceeds the imported quantity during the billing period, the excess quantum shall be carried forward to the next billing period as credited Units of electricity. If the customer falls under ToD tariff ambit, then the electricity imported in any time block, is first compensated with the electricity exported in the same time block. If there is any excess injection in any time block in a billing cycle, off-peak energy rates will be applicable to the net quantum of energy exported as per Sec 11.4 of JERC Solar PV Grid regulations [31]. It is important to note that this is not True Metering, as the value of exported power is always lesser or equal to the value of grid imported power.

As per data published by major solar developers, the total installation costs have been considered Rs 277,500 ($3265) for a 5kW system, which translates to a project cost of Rs 55.5/Wp ($0.65/Wp) [33]. The installation costs include the cost of modules, inverters, solar mounting structures, Balance of System (BoS) equipment including cables, breakers and distribution boxes, as well as labour costs. Lead Acid was the most popular battery type for residential applications. However, in recent times, Lithium-ion batteries, especially their Lithium Ferro Phosphate (LFP) variant, have emerged as a credible alternative because of advantages like higher efficiency and higher lifecycles. For Lithium Ion, publicly available LFP type battery costs were considered, for batteries in the capacity range 1.28 to 5.12 kWh, which provided values in the range of 20,000 – 25,000 Rs/kWh (235.3 – 294.11 $/kWh). For modelling purposes in SAM, an average value of 21852 Rs/kWh (257.09 $/kWh) for LFP batteries has been considered. For Lead Acid batteries, the costs were in the range of 5,556 – 10,000 Rs/kWh (65.36 – 117.641 $/kWh). For modelling in SAM, an average value of 7030 Rs/kWh (82.72 $/kWh) for Lead Acid batteries has been considered. Thus, capital costs of Lead Acid batteries are ~30% of LFP costs.

**Table 2** Electricity tariffs for different periods and tiers for residential and commercial customers in Chandigarh

| Period | Tier | Type of Tariff period | Duration | Max Usage Slab (kWh) | Residential Tariff (USD/kWh) | Commercial Tariff (USD/kWh) |
|---|---|---|---|---|---|---|
| 1 | 1 | Normal period | 0600 Hrs - 1800 Hrs | <=150 | 0.032 | 0.053 |
| 1 | 2 | Normal period | 0600 Hrs - 1800 Hrs | 151-400 | 0.056 | 0.055 |
| 1 | 3 | Normal period | 0600 Hrs - 1800 Hrs | >=400 | 0.064 | 0.069 |
| 2 | 1 | Evening peak load period | 1800 Hrs - 2200 Hrs | <=150 | 0.039 | 0.064 |
| 2 | 2 | Evening peak load period | 1800 Hrs - 2200 Hrs | 151-400 | 0.068 | 0.066 |
| 2 | 3 | Evening peak load period | 1800 Hrs - 2200 Hrs | >=400 | 0.076 | 0.083 |
| 3 | 1 | Off-peak load period | 2200 Hrs - 0600 Hrs | <=150 | 0.029 | 0.048 |
| 3 | 2 | Off-peak load period | 2200 Hrs - 0600 Hrs | 151-400 | 0.051 | 0.050 |
| 3 | 3 | Off-peak load period | 2200 Hrs - 0600 Hrs | >=400 | 0.057 | 0.062 |

## 4. RESULTS AND DISCUSSION

Levelized Cost of Energy (LCOE) is a commonly used metric to evaluate the viability of solar projects. However, LCOE does not consider time variations in energy cost. The LCOE loses its relevance for projects with TOD tariffs [27]. On the other hand, Net Present

Value (NPV) considers the cost, as well as the savings due to energy generation from the project and is applicable for cases where the tariffs vary over time. NPV considers the investment costs, as well as future returns, and discounts future cash flows to their present values, accounting for the time value of money shown in Eq. 7 [26]. Eq 8 can be further broken down into a revenue generation component, which is dependent on net power generation, and ToD tariffs calculated over 1 year, as shown in Eq 8. The latest bank lending rate (r = 8.54%) is derived from the data published by the Reserve Bank of India [34].

In Eqs 8 and 9, $R_n$= Net cash inflow-outflow for year n, $Cost_n$ = Cost in the year n,
$G_t$ = Net Generation at time t, $T_t$ = Tariff for time t,
$N$ = Lifetime of project in years (25 years),
r = discount rate or return that could be earned in alternative investments

$$NPV = \sum_{n=0}^{N} \frac{R_n}{(1+r)^n} \tag{8}$$

$$NPV = \left(\sum_{n=1}^{N} \frac{1}{(1+r)^n} \, \Sigma_{t=0}^{n} G_t \cdot T_t\right) - \sum_{n=0}^{N} \frac{Cost_n}{(1+r)^n} \tag{9}$$

### 4.1. Residential consumer analysis

For our analysis, we compared projects for residential customers using different solar DC capacities. The results as displayed in Fig 5 show that the maximum NPV of $1846.97 is obtained for 6.4 kW solar DC capacity. This graph indicates that if we oversize the DC capacity beyond a certain point, the NPV starts to decrease as the extra capital investment is not compensated through adequate returns. This happens because the state prescribes a Net Metering regime, in which the extra energy sold to grid is not compensated for at the hourly rates at which the electricity is bought, but at the lowest tariff available.

The effect of adding Lead Acid and LFP batteries of differing capacities to a 6.4 kW PV system has also been investigated, and the results are shown in Fig 4. It is clear from this graph that increasing battery capacity has a negative effect on the NPV, so the best NPV in Fig 3 comes from a system with 0 kWh battery (no storage). This signifies that, with current battery pricing and given ToD tariffs, the addition of storage is not financially viable for residential customers in Chandigarh.

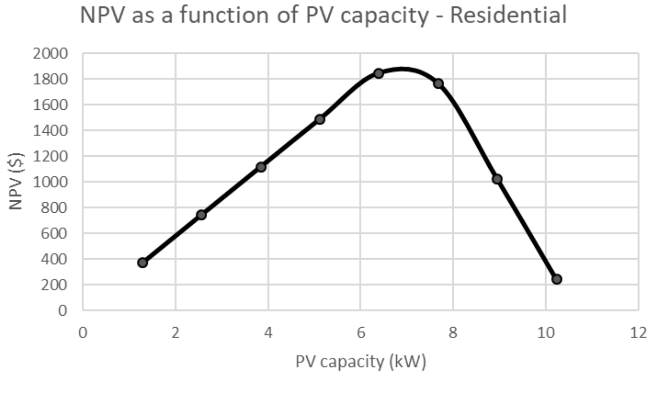

**Fig. 3** NPV as a function of solar DC capacity (kW) for a residential project

The results show that Lead Acid provides better NPV till 4kWh battery capacity, likely because of lower initial costs, but then suddenly falls to give worse results than LFP for larger capacities. At higher battery capacities, the NPV turns negative. LFP batteries can be discharged up to 80% Depth of Discharge (DoD), while Lead Acid cannot be used beyond 50% DoD. As per Table 1, Lead Acid has a higher minimum State of Charge of 50% as compared to 20% for Lithium Ion, which means the Lead Acid batteries store lesser charge for the same battery capacity (kWh). This means that a lot of the actual capacity of the Lead Acid battery remains unused, thus the battery needs to be oversized to meet its performance requirements. This also means that for cycling of the same amount of charge, Lead Acid will need more charge-discharge cycles, thus reducing its lifetime.

LFP batteries typically have a lifecycle of 5000-10000 charge and discharge cycles, compared with Lead Acid which can provide 500-1000 cycles at best. This means that LFP batteries do not need to be replaced before 5-10 years, while Lead Acid batteries do not last beyond 2-4 years. Thus, the replacement frequency for Lead Acid will be much higher than LFP over the lifetime of the project of 25 years. LFP has a higher working voltage of 3.6V as compared to 2V for Lead Acid, which means a smaller number of batteries are required with LFP for the same voltage. LFP has higher charging and discharging rates (C-rates) as compared with Lead Acid. Also, the round-trip efficiency (RTE) of LFP is higher than Lead Acid [13]. The self-discharge rate of Lead Acid is much higher than that of LFP [14].

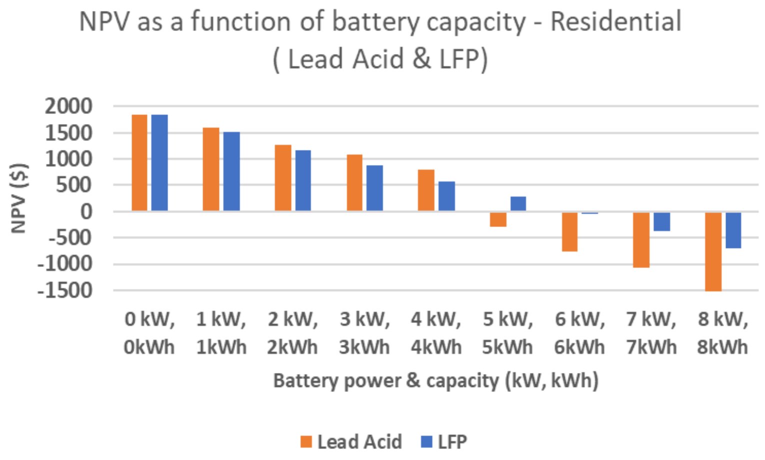

**Fig. 4** Dependence of NPV on battery power & capacity (residential)

### 4.2. Commercial consumer analysis

This study also investigates the optimum PV size in case the installation was commissioned for a commercial customer, instead of a residential one, where the tariffs are as per Table 2 [32]. Also, commercial solar projects are eligible for 40% depreciation in 1st year, and 20% depreciation in 2nd year, which provides corresponding tax savings for the producer [35]. Note that residential producers are not eligible for depreciation benefits. Fig. 5 shows that the optimum solar DC capacity for commercial application is 7.68 kW, as it provides a maximum NPV of $3813. This is much higher than the maximum NPV of $1846 achieved with residential systems. The higher returns for commercial systems are due to the higher tariffs applicable for such consumers, as well as the accelerated depreciation benefits in the initial 2 years.

The returns from adding storage to commercial solar projects were also calculated in the form of NPV, assuming current pricing of @257/kWh for LFP batteries. The results in Fig 6 show that as the battery size increases, the NPV goes down. Hence, the addition of battery capacity at current pricing adds no commercial value, but in fact decreases the returns from the project.

We tested the viability of battery storage for a 50 kW load instead of 5 kW and got the same finding that NPV decreased with addition of battery capacity. It is also seen that Lead Acid battery provides higher returns up to 4 kWh capacity, but LFP has higher NPV at higher capacities. Fig. 6 also compares the respective returns for LFP batteries, if different dispatch algorithms, viz. retail rate dispatch, peak shaving and self-consumption are considered. It is seen that retail rate dispatch gives higher NPV, as opposed to the other dispatch options.

The behaviour of the battery as a function of tariff costs was also analyzed. At every time slot, a decision is taken whether the battery should be charged (or discharged) or it should remain undisturbed. Mirletz [28] has calculated the cost of dispatching power from battery storage in a particular time slot as per Eq 10. $C_{total}$ is the total cost incurred during a particular time slot. The cost $C_{total}$ is calculated for different discharging periods, as well as for the case where the battery is not discharged. Based on the case that gives the lowest cost $C_{total}$, the dispatch (or no dispatch) is scheduled accordingly.

$$C_{total} = C_{grid} + \left(C_{cycle} * n_{cycle}\right) - \left(E_{remaining} * C_{cmarginal}\right) \tag{10}$$

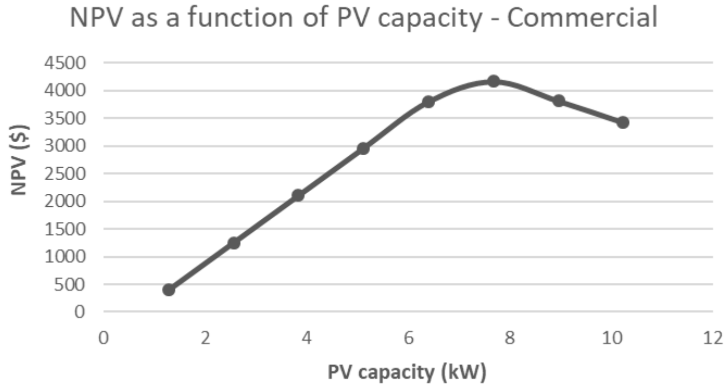

**Fig. 5** NPV as a function of solar DC capacity (kW) for a commercial project

In Figure 7, we can see how the battery algorithm works to minimize customer costs. The power flows are plotted on the primary axis, while the LFP battery State of Charge is plotted on the secondary axis. When solar generation is present, the extra generation is exported to the grid after fulfilling the load, thus earning revenue as per net metering. Since the battery is at full capacity, it is not charged. From 18:00 to 22:00 hours, peak tariffs apply as per Table 2 for commercial consumers. From 18:00 till 22:00, the battery starts to discharge to feed the load so that the import of costly power from the grid can be minimized. In this period, the SOC of the Lithium battery falls from its maximum of 95%

to minimum 20%. Thus, it is demonstrated that the dispatch algorithm ensures import from the grid is minimized, during periods of highest tariffs.

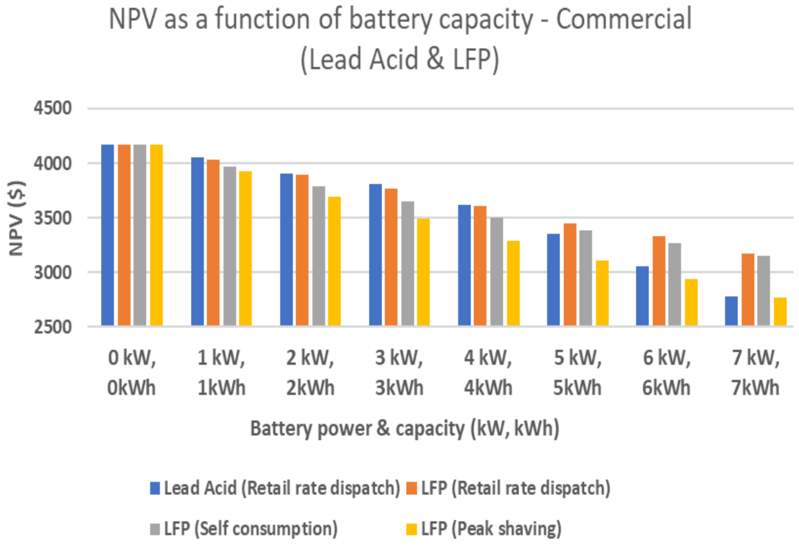

**Fig. 6** Dependence of NPV on battery power & capacity (commercial)

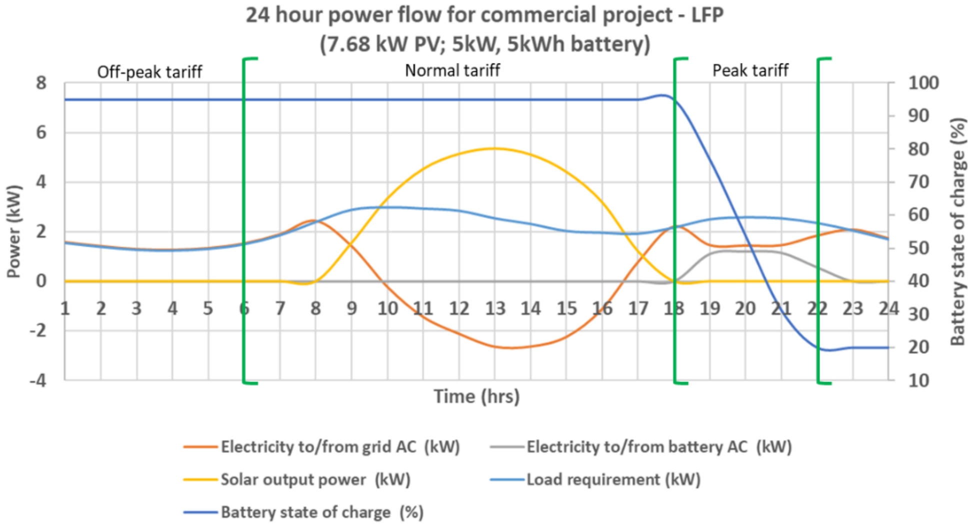

**Fig. 7** State of charge as a function of tariff, solar PV output and load profile

## 5. CONCLUSION

The viability of solar and storage systems for installation at residential and commercial sites respectively, has been assessed in this paper. The optimum solar capacity and the resultant NPV for the given location for residential consumers were calculated. The findings show that with the current residential tariffs, solar installation costs, and battery capital costs, adding battery storage to solar does not make financial sense. This should send a message to regulatory authorities in India who want to encourage consumers to adopt storage in greater numbers, that current regulatory interventions do not provide positive returns for storage integration. This is critical considering the increasing requirement for storage to ensure grid resilience as grid penetration increases. The authorities should look at various policy interventions to make storage financially attractive. These could include the provision of a subsidy for storage, considering that initial costs of storage are quite high, similar to the 30% subsidy provided for residential solar consumers. Another possibility is restructuring the ToD tariffs, especially by increasing the difference between peak and non-peak tariffs, so that price arbitrage of stored power becomes more attractive. This can be a topic of further research, where possible tariff structures with better returns are investigated. True net metering provisions should be applicable, where the cost of exported power is the same as imported power.

Also, for future work, a sensitivity analysis can be done which would study the impact of different combinations of battery prices, tariffs and net metering regulations, to figure out which values give viable returns.

The returns from LFP were compared with those from Lead Acid batteries, and it was noted that the returns are much poorer for Lead Acid at higher battery capacities, even though its cost is ~33% of LFP. The reason for this lies in the relative technical parameters of Lead Acid, including lower round-trip efficiency, higher capacity losses due to only 50% depth of discharge, and lower cycle life. In contrast, for commercial consumers, for the same solar DC capacity, the NPV was much higher, because of accelerated depreciation benefits available in the first two years, as well as higher tariffs.

However, the addition of storage to commercial systems also reduces the returns in the form of NPV. A substantial difference is seen in the returns from residential vs commercial systems with the same load profile, as the highest NPV for a residential customer is $1847 for a 6.6 kW system, while the highest NPV for a commercial customer is $4165 for a 7.7 kW project. The analysis shows that retail rate dispatch gives higher returns as compared with self-consumption and peak shaving. It is also demonstrated that the retail rate algorithm ensures that at every hour, a decision on what battery capacity should be charged or discharged (or kept on standby), based on the cumulative cost of energy for that period, which considers the cost of storage, the cost of imported power, as well as the remaining energy in the battery at the end of that period. The battery SOC is modulated as a function of the prevalent tariff at that time, with the ultimate objective of minimizing energy cost.

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